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1.	Your reference	MPC/8112 GB
2.	Patent application number *(The Patent Office will fill in th...*	0206573.8 21MAR02 E705197-1 D00001 01/7700 0.00-0206573.8
3.	Full name, address and postcode of the or of each applicant *(underline all surnames)*	Blazephotonics Limited Finance Office, University of Bath The Avenue, Claverton Down Bath BA2 7AY United Kingdom 20 MAR 2002
	Patents ADP number *(if you know it)*	8141129001
	If the applicant is a corporate body, give the country/state of its incorporation	United Kingdom
4.	Title of the invention	Photonic crystal fibres
5.	Name of your agent *(if you have one)*	[illegible]
	"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	20 [illegible] Lion Street London WC1R 4PQ
	Patents ADP number *(if you know it)*	174001
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7.	If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application	Number of earlier application / Date of filing *(day/month/year)*
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	Priority documents	
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11.		I/We request the grant of a patent on the basis of this application.
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Photonic crystal fibres

This invention relates to the field of photonic crystal fibres.

Optical fibres are widely used in applications such as telecommunications. Standard optical fibres are typically made entirely from solid materials such as glass, with each fibre having the same cross-sectional structure along its length. Transparent material in one part (usually the middle) of the cross-section has a higher refractive index than material in the rest of the cross-section and forms an optical core. Light is guided in the optical core by total internal reflection from the material surrounding the core, which forms a cladding region. Most standard fibres are made from fused silica glass, incorporating a controlled concentration of dopant, and have a circular outer boundary typically of diameter 125 microns. Standard fibres can be single-mode or multimode.

Different fibres may provide different functions in a system. For example, a length of fibre designed to provide dispersion compensation may be inserted between lengths of standard fibre. Similarly, a length of fibre may act as an optical amplifier or an optical coupler or a sensor or any of a wide range of other devices.

A perennial problem in fibre optics is achieving smooth transitions from one fibre type to another – the "mode-matching" issue. The requirements of a successful transition are insignificant loss (preferably less than 0.1 dB), no conversion between spatial or polarisation modes (unless required), no back reflections and high tensile strength.

A traditional solution is to heat the fibre to its softening temperature and draw it to a taper. The heat source can be a flame or a carbon dioxide laser beam. Mode field transformations can be achieved in which the mode area is reduced or expanded. A related process involves heating a

fibre without tapering it; that causes the core dopants to spread out into the cladding and thus enlarge the area of the guided mode. Disadvantages of this technique are that the fibre has to be stripped for processing and then recoated; this weakens it and is a lengthy and expensive process.

In the past few years a new type of optical fibre has been demonstrated, called the photonic crystal fibre(PCF), holey fibre or microstructured fibre [J. C. Knight et al., Optics Letters v. 21 p. 203]. Typically, a microstructured fibre is made from a single solid material such as fused silica glass, within which is embedded an array of holes. Those 'holes' are usually air holes but may alternatively be, for example, regions of a solid material (e.g. silica doped with impurities to change its refractive index). The holes run parallel to the fibre axis and extend the full length of the fibre. A region of solid material between holes, larger than neighbouring such regions, can act as a waveguiding fibre core. Light can be guided in this core in a manner analogous to total-internal-reflection guiding in standard optical fibres.

One way to provide such an enlarged solid region in a microstructured fibre with an otherwise periodic array of holes is to omit one or more holes from the structure. However, the array of holes need not be periodic for total-internal-reflection guiding to take place (we may nevertheless refer to such a fibre as a photonic-crystal fibre).

Another mechanism for guiding light in microstructured fibres is based on photonic bandgap effects rather than total internal reflection. For example, light can be confined inside a hollow core (an enlarged air hole) by a suitably-designed array of smaller holes surrounding the core [R. F. Cregan *et al.*, Science v. 285 p. 1537]. True guidance in a hollow core is not possible at all in standard optical fibres.

Microstructured fibres can be fabricated by stacking glass elements (rods and tubes) on a macroscopic scale to form a bundle having the required pattern and shape, and holding

them in place while fusing them together. This primary preform can then be drawn into a fibre, using the same type of fibre-drawing tower that is used to draw standard fibre from a standard-fibre preform. The primary preform can, for example, be formed from fused silica elements with a diameter of about 0.8 mm.

The microscopic air channels that run along the entire length of a photonic crystal fibre provide the refractive index profile required to guide light at a central defect, either by a modified form of total internal reflection or by photonic band gap effects. It is known in the prior art to alter the properties of those air holes to alter the properties of the fibre.

Conceptually, the simplest method of controlling the size of an air hole in a PCF is, perhaps, to form a preform having a larger-scale approximation to the desired structure, for example by forming the preform from capillaries having different selected hole diameters. However, in practice, it is costly and relatively difficult to manufacture capillaries of different internal diameters and it is difficult to predict the behaviour of such structures during drawing.

International Patent Application No. PCT/GB00/00599 (The University of Bath) teaches that a region of a PCF may be heat-treated after the PCF has been drawn, in order to collapse holes in the heat-treated region.

International Patent Application No. PCT/US99/18089 (Corning Inc.) teaches that the axial properties of a PCF may be varied, for example by varying gas pressure in the preform during the draw. That variation may, in particular, be used to produce a fibre having a dispersion that alternates between positive and negative dispersion in alternate segments of the fibre, producing a net dispersion of zero over the length of the fibre.

International Patent Application No. PCT/GB00/00600 (The University of Bath) teaches a method of making controlled changes in the structure of a photonic crystal fibre whilst it

is being drawn. The Application describes producing the photonic crystal fibre by stacking an array of silica capillaries inside a silica tube, sealing the tube inside an evacuable cylinder, whilst leaving some or all of the capillaries protruding from the cylinder at each end, and then evacuating the inside of the tube whilst leaving the insides of some or all of the capillaries open to the atmosphere, so that they expand during drawing. In a particular example, the Application teaches producing a highly birefringent PCF by having four of the capillaries terminate within the cylinder, so that they do not expand during drawing, so that the drawn fibre has two-fold rotational symmetry.

We have realised that the prior-art manufacturing methods provide only limited control over the structure of the drawn fibre.

An object of the invention is to provide an improved method of manufacturing a PCF and hence to provide PCFs having improved functionality.

According to the invention there is provided a method of manufacturing a microstructured fibre, comprising:

(i) providing a preform comprising a plurality of elements arranged side-by-side in a bundle, a plurality of the elements being tubes;

(ii) connecting at least one of the tubes to an external pressure-controller by attaching a connector to the tube;

(iii) drawing the preform into the fibre whilst controlling gas pressure in the tube(s) connected to the pump.

By the term 'external pressure-controller', we mean any suitable means for changing the internal pressure of the tubes from atmospheric pressure to another selected value, including, for example, applying a static increased or decreased pressure by means of a piston, but not merely sealing the ends of a tube during drawing to create a pressure difference.

Thus, during drawing of the fibre, the size of individual holes can be controlled by individually addressing each hole

in the preform stack or cane and changing the pressure in that hole. If several holes are addressed simultaneously, then the structure which emerges in the actual fibre can be altered during the drawing process. Radical changes in fibre properties are possible. For example, different devices may be created during the draw along a single length of fibre, with adiabatic transitions provided between each link. Complex arrangements of devices may be produced from a preform comprising a uniform array of tubes.

The external pressure-controller may increase the pressure in the tube above atmospheric pressure. Alternatively, the external pressure-controller may decrease the pressure in the tube below atmospheric pressure. The pressure in the tube may be kept constant throughout the drawing of the fibre. Alternatively, the pressure in the tube may be varied during the draw. Thus variations in the cross-sectional area of the hole may be provided along the length of the drawn fibre. The pressure may be pulsed periodically.

As discussed above, the pressure-controller may be any suitable device, which may apply a static or a varying pressure. The pressure-controller may be, for example, a rotary vane pump, a peristaltic pump or a cylinder piston pump.

Preferably, a plurality of the tubes are connected to the external pressure-controller.

The method may include pressurising further groups, each comprising at least one of the tubes, to a second pressure or pressures, for example by connecting them to further external pressure-controllers. For example, preferably the method includes connecting at least one (preferably a plurality) of the tubes to a second external pressure-controller and the method may include connecting at least one (preferably a plurality) of the tubes to a third external pressure-controller.

Preferably, the method includes the step of producing a plurality of devices arranged axially along the PCF by varying

over time the pressure applied to the tube or tubes. It may be that each of the plurality of devices is the same; the method thus provides a method of mass-producing large numbers of a particular device, spaced at intervals along a single fibre; after production, the devices may then be separated (e.g. by cleaving the fibre). Alternatively, the plurality of devices may comprise a plurality of different devices; thus complex optical effects such as signal processing may be achieved in a single fibre.

The method may include the step of varying over time the rate at which the fibre is drawn from the preform.

The method may include the step of varying over time the preform feed rate. The preform feed rate may even be negative for brief periods of time, such that the preform is being pulled in a direction opposite to the direction in which the fibre is being drawn.

The method may include the step of varying over time the furnace temperature.

Preferably, the pressurisation results in at least one elongate hole formed in the drawn fibre having a different transverse area in one part of the fibre from its transverse area in another part of the fibre. At least one hole may be collapsed completely over a length of the fibre. Such an arrangement may be used for example to create and destroy local cores over particular lengths of the fibre. Similarly, creating and destroying holes adjacent to a core region may be used to create lengths of fibre having an enlarged or reduced core.

Preferably, the pressurisation results in at least one part of the dielectric matrix region having a different transverse area in one part of the fibre from its transverse area in another part of the fibre.

The pressurisation may result in, in a transverse cross-section of the drawn fibre, a plurality of concentric regions, wherein alternate adjacent regions are of a higher and a lower effective refractive index respectively.

The pressurisation may result in the drawn fibre being a W-profile fibre over at least part of its length.

The pressurisation may result in the drawn fibre comprising a long period grating.

The variation in pressurisation may result in a change in the symmetry of the fibre, such that a portion of the fibre is birefringent.

Preferably, two portions of the fibre are birefringent, but their principal polarisation axes are rotated relative to each other by the variation in pressurisation.

Also according to the invention there is provided a photonic crystal fibre comprising a core region and a cladding region comprising a plurality of elongate holes, the fibre comprising a first region of its length in which the holes are arranged in a first pattern having at-most-two-fold rotational symmetry, such that the fibre has in the first region a fast polarisation axis and a slow polarisation axis, and a second region of its length in which the holes are arranged in a second pattern having at-most-two-fold rotational symmetry, such that the fibre in the second region has a fast polarisation axis and a slow polarisation axis, the polarisation axes in the second region being rotated relative to the polarisation axes in the first region, the fibre further comprising a transition region, between the first region and the second region, in which the at least one of the hole changes in cross-sectional area so that the first pattern changes into the second pattern.

Thus, a PCF with low birefringence may be turned adiabatically into a fibre with high birefringence. A twist-compensated PM fibre link (designed to have zero DGD) may be made by simply altering the distribution of pressure in the holes part-way through the draw so as to make the slow axis into a fast axis and vice-versa.

Further portions of the fibre may be birefringent and have rotated polarisations. Any suitable photonic crystal

structure may be used to provide birefringence; for example, the structure may be based on a square lattice.

The variation in pressurisation may result in a change in core size in the drawn fibre, such that at least one of the devices comprises a fibre portion having a larger core region and at least one of the devices comprises a fibre portion having a smaller core region; thus, for example, a large core may be turned into a small core by increasing the pressure and collapsing; a similar effect can be produced by altering the drawing tension.

Also according to the invention there is provided a photonic crystal fibre comprising a core region and a cladding region comprising a plurality of elongate holes, the fibre comprising a region of its length in which the holes adjacent to the core region are of a larger cross-sectional area, and the core region is of a smaller cross-sectional area, than in an adjacent length of the fibre, such that, in use, the fibre has an increased nonlinear response to propagating light in that region of the fibre.

The variation in pressurisation may result in a change in core size, such that at least one of the devices is a nonlinear fibre portion, comprising a core region that is sufficiently small for significant nonlinear optical effects to occur in use. Thus, ultra-small core fibre may be produced in the centre of an otherwise medium-core fibre link - that may allow efficient nonlinear functions to be built seamlessly into a telecommunications system. Because there is no requirement to strip and recoat the fibre, it should have unimpaired tensile strength.

The drawn fibre may comprise a plurality of core regions. Preferably, the variation results in the separation of at least two of the cores being reduced in a region of the fibre, such that at least one of the devices comprises an optical coupler comprising the reduced separation region. Preferably, the devices comprise two optical couplers that form a Mach-Zehnder interferometer. Thus, in-line Mach-Zehnder

interferometers may be produced by a simple process of reducing the air hole size between two cores at two points along a dual-core length.

Preferably, the devices comprise a network of switches and/or filters formed from the plurality of couplers.

Also according to the invention there is provided a photonic crystal fibre comprising at least three core regions and a cladding region comprising a plurality of elongate holes, the fibre comprising at least one coupler between a first pair of the core regions and at least one coupler between a second, different, pair of the core regions, each coupler comprising a region of the fibre in which the cross-sectional area of the holes between the coupled cores is smaller than in adjacent lengths of the fibre, such that the cores are brought closer together.

Such an arrangement would have considerable advantages over taper post-processing, where it is very difficult (if not impossible) to heat-treat selected holes while keeping the rest unaffected. In-line fabrication allows couplers to be created between any group (of two or more) cores while leaving the others unaffected; further down the fibre couplers may be created between different cores.

The fibre may comprise more than two cores. Preferably, the variation results in the separations of the cores being reduced over a plurality of portions of the fibre to form optical couplers between each of the more than two cores. Thus, still more complex networks of devices may be produced.

Preferably, transition regions formed between each of the optical devices are sufficiently gradual to be adiabatic. Thus, in one draw, a fibre may be produced with many different properties at different positions along its length, all connected by seamless low-loss transitions.

The condition of the draw may be oscillated between two states over time to form a transition region, the first state being matched to the mode of a first of the optical devices and the second state being matched to the mode of a second of

the optical devices; for example, one state may be arranged to match a single-mode fibre and the other state may be arranged to match a speciality fibre such as a dispersion compensating fibre (DCF), an amplifier or a highly nonlinear fibre.

Also according to the invention there is provided a photonic crystal fibre comprising a core region and a cladding region comprising a plurality of elongate holes, the fibre comprising a first length in which the holes are arranged in a first transverse pattern providing a first function, a second length in which the holes are arranged in a second transverse pattern providing a second function, and a transitional length along which at least one of the holes oscillates in cross-sectional area such that the holes oscillate between the first pattern and the second pattern, such that, in use, light is coupled in the transitional length between a mode guided in the first length and a mode guided in the second length.

Similarly, the method may include the step of manufacturing twist-compensated DGD-free fibre by oscillating the structure to and fro periodically (the period being perhaps of a few metres) along the length of the drawn fibre. That would make the exact cutting of length - to achieve DGD-free operation - very easy since an integral number of periods is needed. The accuracy of the actual dispersion would then be within $100 \times dL/L$ percent of the required value.

Similarly, at least one of the holes oscillates between a first value and a second value, such that the holes oscillate between a first pattern and a second pattern and thus substantially avoid an unwanted phase-matching condition.

Also according to the invention there is provided a photonic crystal fibre comprising a core region and a cladding region comprising a plurality of elongate holes, the fibre comprising a length in which the cross-sectional area of at least one of the holes oscillates between a first value and a second value, such that the holes oscillate between a first pattern and a second pattern and thus substantially avoid an unwanted phase-matching condition.

The method may include the step of producing a DCF with graded properties that match the dispersion curve in standard telecomms fibre over the telecommunications bands (dispersion, slope, curvature and slope of curvature etc.). That may be achieved by choosing the functional shape along the length of the fibre appropriately. The dependence of dispersion curve on geometry may be calculated, and used to solve an integral equation for the desired link properties - the required length dependence is given by a function inside the integral.

Parameters of the draw may be controlled during manufacture to produce a desired structure by feedback from direct measurement of the drawn fibre (e.g. the diameter of a hole or a plurality of holes).

Preferably, the method includes the step of calibrating the relationship between parameters of the draw and parameters of the drawn fibre.

Preferably, the method further comprises varying parameters of the draw according to the calibration results to produce a fibre having a selected structure. Thus, the relationship between draw parameters such as pressure, temperature and draw speed and fibre parameters such as hole size and pitch are preferably determined in prior calibration runs. Such calibration may be achieved, for example, by carrying out a large number of sample draws and measuring the results of varying, at any one time, one or more parameters of the draw.

Preferably, the pressure applied to the or each hole is controlled by a digital signal; that is, the pressure may be applied in bursts or pulses of a fixed pressure, with more pulses being applied in a given time interval to apply, effectively, a higher pressure (of course, alternatively an analogue, continuously varying signal may be used).

The elements of the preform may be selected according to the structure desired in the drawn fibre. For example, all of the elements of the preform may be tubes, which may be arranged to provide a triangular lattice of holes in the drawn

fibre. At least one of the elements of the preform may be a solid rod; use of such a rod allows for the manufacture of more complex microstructure by providing a larger region of solid dielectric material in the drawn fibre than is provided by a capillary. The preform may further comprise a larger tube that surrounds the bundle of tubes and forms a jacket region in the drawn fibre.

The drawn microstructured fibre may be arranged to guide light in a core by photonic-band-gap guidance. Alternatively, the drawn microstructured fibre may be arranged to guide light in a core by index-guidance; the core may be drawn from a solid rod in the preform.

The tubes of the preform may be connected to different pressures in any suitable way; examples of possible arrangements are set out below.

A portion of the preform may be retained undrawn during the drawing of the fibre and individual connections may be made directly, for example via a hose, from one or more external pressure-controllers to each tube or tubes to be pressurised by that pressure-controller.

Alternatively, a connector may be provided to connect the tubes to the external pressure-controller.

Also according to the invention there is provided a connector for connecting a preform, which is for a microstructured fibre and which comprises a plurality of tubes, to a pressure source, the connector comprising a plurality of apertures arranged to receive the ends of one or more of the tubes and a plurality of chambers in which one or more of the tubes passing through the apertures terminate, each chamber being connectable to a pressure source.

Preferably, different ones of the chambers are connectable, individually or in groups, to different pressure sources. Preferably, each chamber is in fluid communication with a passage that is connectable to the pressure source. More preferably, the passage terminates in a valve.

The chambers may be distributed in the connector in a plane substantially orthogonal to the direction in which the tubes are intended to pass through the apertures; thus, the chambers may be side-by-side in that plane. The chambers may be adjacent to the apertures. Preferably, the chambers are recesses in a side of the connector. The passages may pass from the chambers to the opposite side of the cap; alternatively, the passages may pass to another side of the cap. Preferably, the recesses are arranged to be sealed around the ends of the tubes.

The chambers may be distributed in the connector along the direction in which the tubes are intended to pass through the aperture; thus at least one of the tubes may pass through one or more chamber and terminate in a chamber arranged further from the aperture than the chamber(s) through which that tube passes. Such a connector is designed to receive preform tubes of two or more different lengths, such that the tubes of each length, or within different ranges of lengths, terminate in a different chamber.

A method, described above as being according to the invention, may thus further comprise the step of placing a connector, such as is described above as being according to the invention, over the end of the preform such that the ends of at least some of the tubes pass through the apertures and into the chambers, connecting the chambers to one or more external pressure-controllers and pressuring the tubes to one or more selected pressure during the draw.

Also according to the invention, there is provided a microstructured fibre manufactured according to a method described above as being according to the invention.

Embodiments of the invention will now be described, by way of example only, with reference to the drawings, of which:

Fig. 1 is an example of a preform for use in a method according to the invention;

Fig. 2 is a first arrangement for pressurising the preform of Fig. 1;

Fig. 3 is a second arrangement for pressurising the preform of Fig. 1, show (a) in vertical cross-section and (b) in plan from underneath;

Fig. 4 is a third arrangement for pressurising the preform of Fig. 1;

Fig. 5 is a fibre according to the invention having polarisation axes that change adiabatically along the length of the fibre;

Fig. 6 is a fibre according to the invention having a small, nonlinear core;

Fig. 7 is a fibre according to the invention that includes a network of Mach-Zehnder interferometers between its cores;

Fig. 8 is a fibre according to the invention in which propagating is coupled between two states.

A typical preform 20 (Fig. 1) for a photonic crystal fibre, of a type well known in the prior art, comprises a bundle of thin tubes 30, arranged in a triangular lattice pattern and held together inside a large tube 5. At the centre of the preform 20, a solid cane 15 is provided in place of a tube 30 in the lattice arrangement. A photonic crystal fibre 10 is drawn from the preform in the usual way. In the drawn fibre 10, tubes 30 form a cladding region comprising a plurality of elongate holes embedded in a silica matrix. Cane 15 forms a solid, elongate core region within the fibre. large tube 5 forms a jacket region that protects the fibre. In this example, light is guided in the core region by total internal reflection from the cladding region, which has a lower effective refractive index than the refractive index of the core region.

In a first method of individually pressurising holes in the preform 20 during drawing into fibre 10 (Fig. 2), tubes 30 are arranged to protrude from jacket tube 5 in preform 20. hoses 40 are attached to selected ones of the protruding ends of tubes 30; hoses 40 are held in place by O-rings 50. Hoses

40 are connected at their other ends to external pressure-controllers (not shown).

During drawing of fibre 10 from preform 20, the pressures inside tubes 30, and hence the holes into which they are drawn, is varied by varying the pressure produced by the external pressure-controllers in hoses 40. The pressure in hoses 40 is varied in time and also different pressures are applied at any one time to different ones of hoses 40. Thus the holes produced in the cladding region of the drawn fibre 10 vary in their cross-sectional areas both along the fibre and from hole to hole in fibre transverse cross-sections.

In an alternative method (Fig. 3), as an alternative to connecting hoses directly to preform 10, an intermediate connector 100 is used.

Connector 100 is a flat disk into which have been cut a number of chambers in the form of recesses 110, 115, 120, 125. Recesses 110, 115, 120, 125 are arranged to receive the ends of tubes 30 where they protrude from the preform 20. Recesses 110 are each arranged to receive the end of one of tubes 30. Recesses 115 are each arranged to receive the end of two of tubes 30. Recess 120 are each arranged to receive the ends of groups of seven of tubes 30 (or six plus cane 15). Recess 125 are each arranged to receive the ends of groups of five of tubes 30. The tubes 30 are sealed in the recesses 110, 115, 120, 125 by means of a gasket.

Passages 130 pass through connector 100 to valves 140. Prior to drawing, hoses 40 are attached to valves 140. The other ends of hoses 40 are attached to external pressure-controllers, as before. In this arrangement, the pressure produced by the controllers affects the pressure in tubes 30 by changing the pressures in recesses 110, 115, 120, 125. Thus, for example, all seven tubes in each recess 120 are pressurised to the same pressure, whereas the pressures in tubes in recesses 110 may be varied individually.

An alternative form of connector is shown in Fig. 4. In this example, preform 20 is arranged so that different ones of

tubes 30 protrude from preform 20 by different lengths. Intermediate connector 200 comprises three chambers 210, 220, 230, arranged in a stack. Each chamber has a valve 240 to which hoses 40 are connected. The other ends of hoses 40 are attached to external pressure-controllers, as before.

Each chamber has a plurality of holes (not shown) in its base; each hole is either sealed or contains an O-ring, through which one of tubes 30 passes. The tubes 30 are divisible into three length ranges. The shortest terminate in the bottom chamber 210 in the stack. The middle-length tubes pass completely through the bottom chamber 210 and terminate in middle chamber 220. the longest tubes pass through chambers 210, 220 and terminate in chamber 230.

During drawing, each of chambers 210, 220, 230 is pressurised (or partially or completely evacuated) to a different pressure. The size of each hole produced in the final fibre depends on the pressure in the particular chamber in which the tube 30 that formed the hole terminates.

The cross-sectional and axial shape and distribution of the holes in fibre 10 will depend on how the pressure in tubes 30 differs from tube to tube and changes over time. In the steady state, the relationship between hole size and hole pressure is given by

$$p = \frac{\sigma}{r},$$

where σ is surface tension of the silica matrix material and r is the radius of the hole.

For any particular device to be provided in fibre 10, the sites of holes that are to be enlarged or reduced are identified and the corresponding pressures required in tubes 30, to produce the required hole diameters, are calculated by computer according to the above relationship. The computer is programmed with the desired transverse hole diameters and their variation with time. The computer is arranged to

control the pressures supplied by the external pressure-controllers, according to the relationship given above, to produce the desired hole shapes. A calibration run is carried out to confirm that the fibre material behaves as predicted during the draw and any necessary parametric adjustments made.

Figs. 5 to 8 are examples of devices that can be produced by examples of the method of the invention.

An example of a fibre produced by the method is photonic crystal fibre 300 (Fig. 5), which exhibits substantially no differential group delay (DGD). A fibre having that property is described in co-pending British Patent Application No. 0200603.9 (BlazePhotonics Limited), which is hereby incorporated herein by reference. In that patent, DGD is avoided by providing a 90 degree twist, or a series of twists forming a rocking filter, halfway along a photonic crystal fibre, so that the polarisation mode of propagating light and the polarisation axes of the fibre are rotated relative to each other. Thus any DGD experienced by light propagating in the first half of the fibre is cancelled out by propagation through the second half of the fibre.

In the fibre 300 of Fig. 5, the same effect is achieved, during the draw and without the need for twisting the fibre. The polarisation axes of fibre 300 are gradually swapped by changing the size of hole in the cladding region of the fibre 300, by changing the pressurisation of the holes during the draw in accordance with the invention. The fibre 300 comprises a cladding region comprising a square array of holes 330 formed in matrix material 310, and a solid silica core region 330. In transverse plane A-A' (Fig. 5(ii)), the square lattice pattern of holes 320 results in there being eight holes adjacent to the core 330. Of those eight, four holes 360 at the corners of the square are the same size as holes 320. Holes 340 on opposite sides of the core region 330 are enlarged relative to holes 320. The remaining two holes 350 have a cross-sectional area that is reduced relative to holes 320. The enlarged holes 340 are produced by applying a higher

pressure during a first period of drawing to the ones of tubes 30 from which they are formed; the reduced holes 350 are produced by applying a lower pressure to the corresponding ones of tubes 30. The fibre thus has a fast polarisation axis passing through enlarged holes 340 and a slow polarisation axis in a direction orthogonal to the fast axis.

Once a desired length of fibre 300 has been drawn with the hole configuration of Fig. 5(ii), drawing is continued but the pressure in holes 340 is reduced and the pressure in holes 350 is increased. Holes 340, 350 thus gradually change size until at plane B-B' (Fig. 5 (iii))at what will be the centre of the fibre 300, they are the same size as holes 320, such that the cladding region is a uniform lattice. The change in applied pressure is continued so that at plane C-C', holes 340 are the size at which holes 350 were in plane A-A' and vice versa. The rest of fibre 300 is drawn with fixed pressures, so that from plane C-C' onwards, the fibre has a fast polarisation axis through holes 350 and a slow polarisation axis through holes 340. DGD experienced by light propagating in fibre 300 to plane B-B' is thus cancelled out by propagation onwards from plane B-B' in the half of the fibre in which the polarisation axes have been reversed. The distance from plane A-A' to B-B' and from B-B' to C-C' is approximately 1 m, which is sufficiently long to provide a lossless (adiabatic) transition.

Another example of a fibre produced by the method is photonic crystal fibre 400 (Fig 6.), which includes a small nonlinear core region 450. In transverse planes A-A' and C-C' (Fig. 6(ii),(iii)) the fibre has a uniform cross-section, comprising a core region 430 surrounded by a cladding region comprising holes 420 arranged on a triangular lattice pattern in matrix material 410. Core region 430 has a diameter of about 5 microns. During drawing of fibre 400, beyond plane A-A', the pressure in the six holes 440, which are adjacent to the core region 430, is increased relative to the pressure in holes 420. Holes 440 expand relative to holes 420 (Fig.

6(iii)) and the expansion forces silica material out of the core region, forming a small core region 450 of diameter about 2 microns. The holes 440 reach a maximum size at plane B-B' and then the pressure is reduced again so that the core region returns at plane C-C' to the size it had in plane A-A'.

Large holes 440 concentrate light in small core region 450 and nonlinear effects, such as self-phase modulation and self-focusing, result for sufficiently high light intensities.

Another example of a fibre produced by the method is photonic crystal fibre 500 (Fig. 7), which comprises a pair of Mach-Zehnder interferometers formed between its cores by the method of the invention. The fibre comprises a cladding region formed from a triangular lattice of holes 502 embedded in a silica matrix 501 and nine core regions (including cores 510, 520 and 530) arranged on a square lattice and formed where holes are missing in the triangular cladding lattice. One Mach-Zehnder interferometer comprises a pair 540, 542 of couplers formed between cores 520, 530 and the other comprises a pair 550, 552 of couplers formed between cores 510, 520. A long-period grating 545 is formed on fibre 530 between couplers 540, 542 and another long-period grating 555 is formed on fibre 510 between couplers 550, 552.

Each coupler 540, 542 is formed by reducing the pressure in the holes between cores 520 and 530 during the draw so that those holes are reduced in diameter and cores 520, 530 are brought closer together (Fig. 7 (iii)). Similarly, each coupler 550, 552 is formed by reducing the pressure in the holes between cores 510 and 520 so that those holes are reduced in diameter and cores 510, 520 are brought closer together (Fig. 7 (iv)).

Thus multiple waveguides are provided in fibre 500 in the form of the fibre cores and signals may readily be transferred between cores 510, 520, 530 via the Mach-Zehnder interferometers.

It will readily be appreciated that other, more complex, networks of devices may be formed in fibre 500 by forming

couplers between others of the nine core regions at different points along the fibre length.

Another example of a fibre produced by the method is photonic crystal fibre 600 (Fig. 8), which comprises a length of highly birefringent fibre and a length of nonlinear fibre and a region between those lengths in which light is coupled adiabatically between the two fibre types.

Fig. 8 (ii) to (vii) are cross sections through fibre 600 taken at 1 m intervals between transverse plane A-A' and transverse plane B-B'. Fibre 600 comprises a core region 630, surrounded by a cladding region comprising holes 620 embedded in silica matrix 610.

In Fig. 8 (ii) and (iii), fibre 600 has a highly birefringent structure, resulting from two enlarged holes 640, positioned adjacent to and on opposite sides of the core region 630, which are produced by providing increased pressure in the tubes 30 forming those holes during drawing from the preform.

In Fig. 8 (vi) and (vii), fibre 600 has a highly nonlinear structure resulting from a small core region 650 and six adjacent enlarged holes 660, (in a similar arrangement to the embodiment of Fig. 6 (iii)).

In Fig. 8 (iv), (v) and (vi), the structure of fibre 600 oscillates between the highly birefringent structure and the nonlinear structure. That oscillation is achieved by varying during the draw the pressure in the four holes adjacent to the core region of the fibre that are not holes 640. The changes in hole size and core size along this transitional length of fibre are very gradual and light propagation is essentially loss-less.

Light propagating in the fibre 600 is thus adiabatically coupled between a mode that propagates without loss in the highly birefringent length of the fibre and a (different-shaped) mode that propagates without loss in the highly nonlinear length of the fibre. As light passes along the oscillating structure, more and more light is coupled from the

mode of the highly birefringent region to the mode of the highly nonlinear region.

Set out above are some examples of devices that may be produced in a method according to the invention. It is envisaged that a great many other devices may also be produced according to the method, due to the great range of possible fibre structures that may result from controlling pressure in selected holes of a preform for a microstructured fibre. Also, it may be that the devices described above may be made by methods not according to the invention, for example by post-processing a microstructured fibre (for example, by heat treatment).

Claims

1. A method of manufacturing a microstructured fibre, comprising:

(i) providing a preform comprising a plurality of elements, arranged side-by-side in a bundle, a plurality of the elements being tubes;

(ii) connecting at least one of the tubes to an external pressure-controller by attaching a connector to the tube;

(iii) drawing the preform into the fibre whilst controlling gas pressure in the tube(s) connected to the pressure-controller.

2. A method as claimed in claim 1, in which the external pressure-controller increases the pressure in the tube above atmospheric pressure.

3. A method as claimed in claim 1, in which the external pressure-controller decreases the pressure in the tube below atmospheric pressure.

4. A method as claimed in any preceding claim, in which the pressure in the tube is kept constant throughout the drawing of the fibre.

5. A method as claimed in any of claims 1 to 3, in which the pressure in the tube is varied during the draw.

6. A method as claimed in claim 5, in which the pressure is pulsed periodically.

7. A method as claimed in any preceding claim, in which a plurality of the tubes are connected to the external pressure-controller.

8. A method as claimed in any preceding claim, the method including the step of pressurising further groups, each comprising at least one of the tubes, to a second pressure or pressures.

9. A method as claimed in any preceding claim, the method including the step of varying over time the rate at which the fibre is drawn from the preform.

10. A method as claimed in any preceding claim, the method including the step of varying over time the preform feed rate.

11. A method as claimed in any preceding claim, the method including the step of varying over time the furnace temperature.

12. A method as claimed in any preceding claim, in which the pressurisation results in at least one elongate hole formed in the drawn fibre having a different transverse area in one part of the fibre from its transverse area in another part of the fibre.

13. A method as claimed in any preceding claim, in which the pressurisation results in at least one part of the dielectric matrix region having a different transverse area in one part of the fibre from its transverse area in another part of the fibre.

14. A method as claimed in claim 13, in which at least one hole is completely collapsed over a length of the fibre.

15. A method as claimed in any preceding claim, in which the pressurisation results in, in a transverse cross section of the drawn fibre, a plurality of concentric regions, wherein alternate adjacent regions are of a higher and a lower effective refractive index respectively.

16. A method as claimed in any preceding claim, in which the pressurisation results in the drawn fibre being a W-profile fibre over at least part of its length.

17. A method as claimed in any preceding claim, the method including the step of producing a plurality of devices arranged axially along the PCF by varying over time the pressure applied to the tube or tubes.

18. A method as claimed in any preceding claim, in which the pressurisation results in the drawn fibre comprising a long period grating.

19. A method as claimed in any preceding claim, in which the variation in pressurisation results in a change in the symmetry of the fibre, such that a portion of the fibre is birefringent.

20. A method as claimed in claim 19, in which two portions of the fibre are birefringent and their principal polarisation axes are rotated relative to each other by the variation in pressurisation.

21. A method as claimed in claim 20, in which the distribution of pressure in the holes is altered part-way through the draw so as to make the slow axis into a fast axis and vice-versa.

22. A method as claimed in any of claims 19 to 21, in which further portions of the fibre may be birefringent and have rotated polarisations.

23. A method as claimed in any preceding claim, in which the variation in pressurisation results in a change in core size in the drawn fibre, such that the fibre comprises a fibre portion having a larger core region and a fibre portion having a smaller core region.

24. A method as claimed in any preceding claim, in which the variation in pressurisation results in a change in core size, such that the fibre comprises a nonlinear fibre portion, comprising a core region that is sufficiently small for significant nonlinear optical effects to occur in use.

25. A method as claimed in any preceding claim, in which the drawn fibre comprises a plurality of core regions.

26. A method as claimed in claim 25, in which the variation results in the separation of at least two of the cores being reduced in a region of the fibre, such that the fibre comprises an optical coupler comprising the reduced separation region.

27. A method as claimed in claim 26, in which the fibre comprises two such optical couplers that form a Mach-Zehnder interferometer.

28. A method as claimed in claim 26 or claim 27, in which the fibre comprises a network of switches and/or filters formed from a plurality of such couplers.

29. A method as claimed in claim 25, in which the fibre comprises more than two cores.

30. A method as claimed in claim 29, in which the variation results in the separations of the cores being reduced over a plurality of portions of the fibre to form optical couplers between each of the more than two cores.

31. A method as claimed in any preceding claim, in which a transition region formed between each of a plurality of optical devices formed in the fibre is sufficiently gradual to be adiabatic.

32. A method as claimed in any preceding claim, in which the condition of the draw is oscillated between two states over time to form a transition region, the first state being matched to the mode of a first optical device comprised within the fibre and the second state being matched to the mode of a second of optical device comprised within the fibre.

33. A method as claimed in any preceding claim, the method includes the step of manufacturing twist-compensated DGD-free fibre by oscillating the structure to and fro periodically along the length of the drawn fibre.

34. A method as claimed in any preceding claim, in which the pressure is oscillated during the draw to avoid unwanted nonlinear effects by oscillating the fibre structure around a desired structure that satisfies an unwanted phase-matching condition.

35. A method as claimed in any preceding claim, in which the method includes the step of producing a DCF with graded properties that match the dispersion curve in standard telecomms fibre over the telecommunications bands.

36. A method as claimed in any preceding claim, in which the method includes the step of calibrating the relationship between parameters of the draw and parameters of the drawn fibre.

37. A method as claimed in claim 36, in which the method further comprises varying parameters of the draw according to the calibration results to produce a fibre having a selected structure.

38. A method as claimed in any preceding claim, in which the pressure applied to the or each hole is controlled by a digital signal.

39. A method as claimed in any preceding claim, in which a portion of the preform is retained undrawn during the drawing of the fibre, and individual connections are made directly, for example via a hose, from one or more external pressure-controllers to each tube or tubes to be pressurised by that pressure-controller.

40. A method as claimed in any of claims 1 to 38, in which a connector is provided to connect the tubes to the external pressure-controller.

41. A connector for connecting a preform, which is for a microstructured fibre and which comprises a plurality of tubes, to a pressure source, the connector comprising a plurality of apertures arranged to receive the ends of one or more of the tubes and a plurality of chambers in which one or more of the tubes passing through the apertures terminate, each chamber being connectable to a pressure source.

42. A connector as claimed in claim 41, in which different ones of the chambers are connectable, individually or in groups, to different pressure sources.

43. A connector as claimed in claim 41 or claim 42, in which each chamber is in fluid communication with a passage that is connectable to the pressure source.

44. A connector as claimed in any of claims 41 to 43, in which the chambers are distributed in the connector in a plane substantially orthogonal to the direction in which the tubes are intended to pass through the apertures.

45. A connector as claimed in claim 44, in which the chambers are adjacent to the apertures.

46. A connector as claimed in claim 45, in which the chambers are recesses in a side of the connector.

47. A connector as claimed in any of claims 41 to 45, in which the chambers are distributed in the connector along the

direction in which the tubes are intended to pass through the aperture.

48. A method as claimed in any of claims 1 to 40, further comprising the step of placing a connector as claimed in any of claims 41 to 47 over the end of the preform such that the ends of at least some of the tubes pass through the apertures and into the chambers, connecting the chambers to one or more external pressure-controllers and pressuring the tubes to one or more selected pressure during the draw.

49. A method substantially as herein described with reference to the accompanying drawings.

50. An optical device as herein described, with reference to the accompanying drawings.

FIG. 1

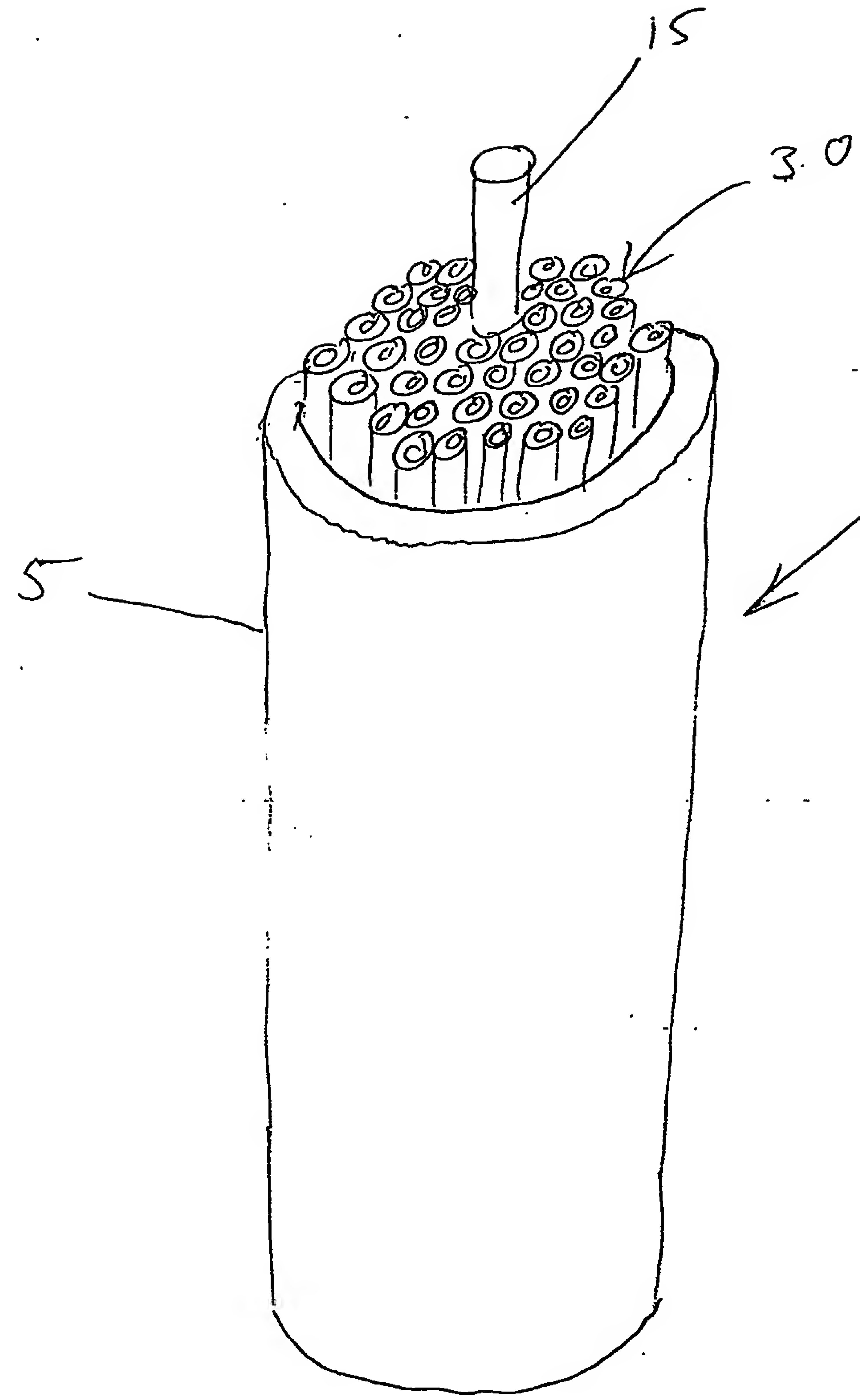
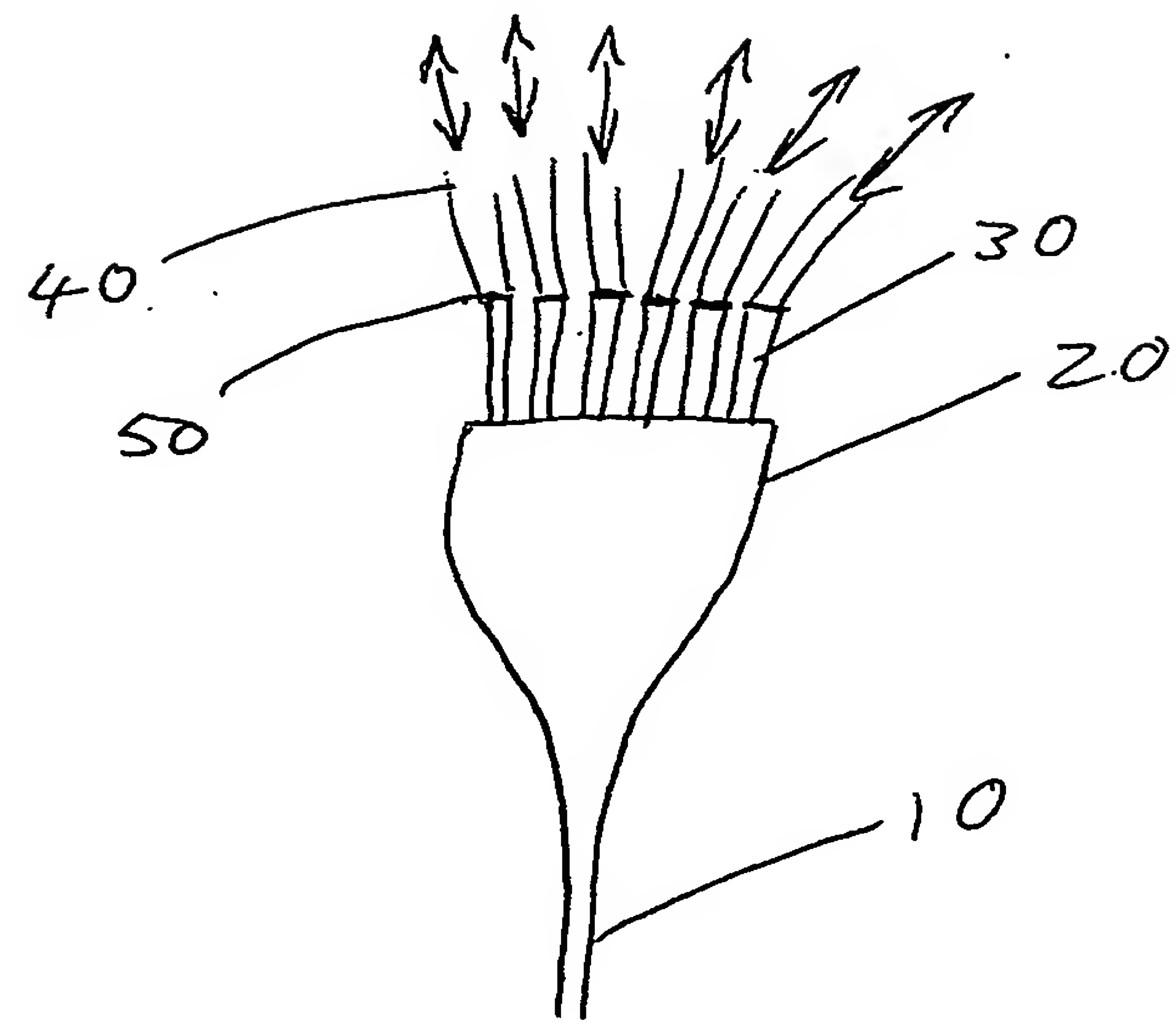


FIG. 2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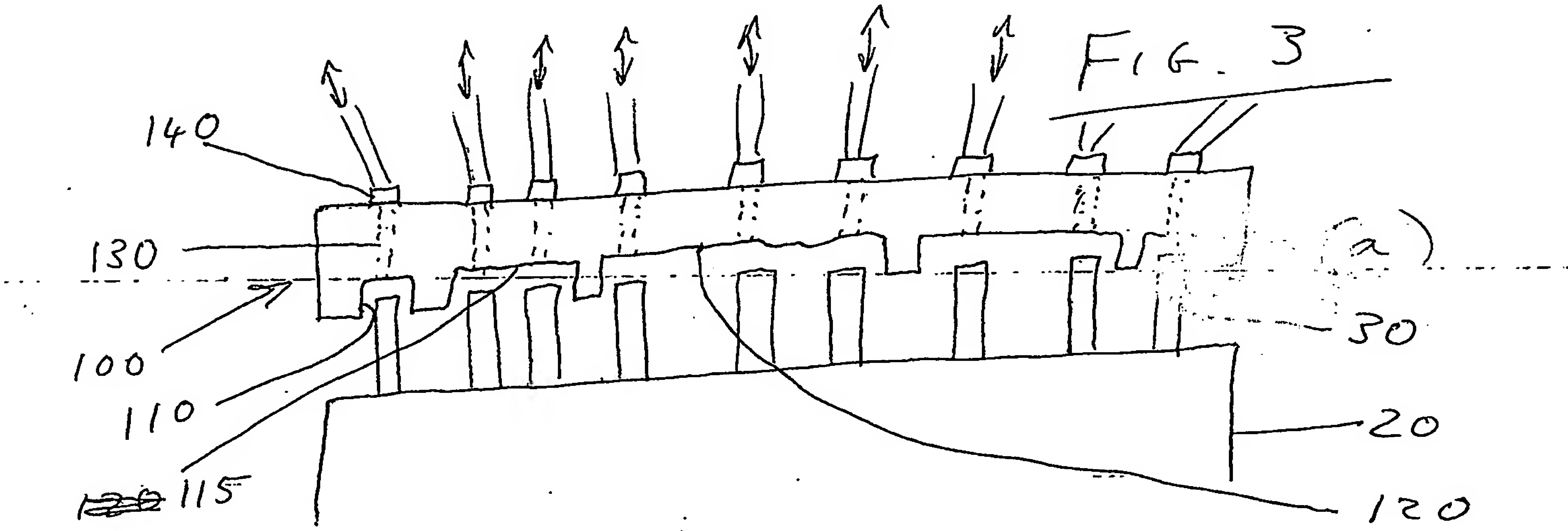
10

FIG. 3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30
110
20
115
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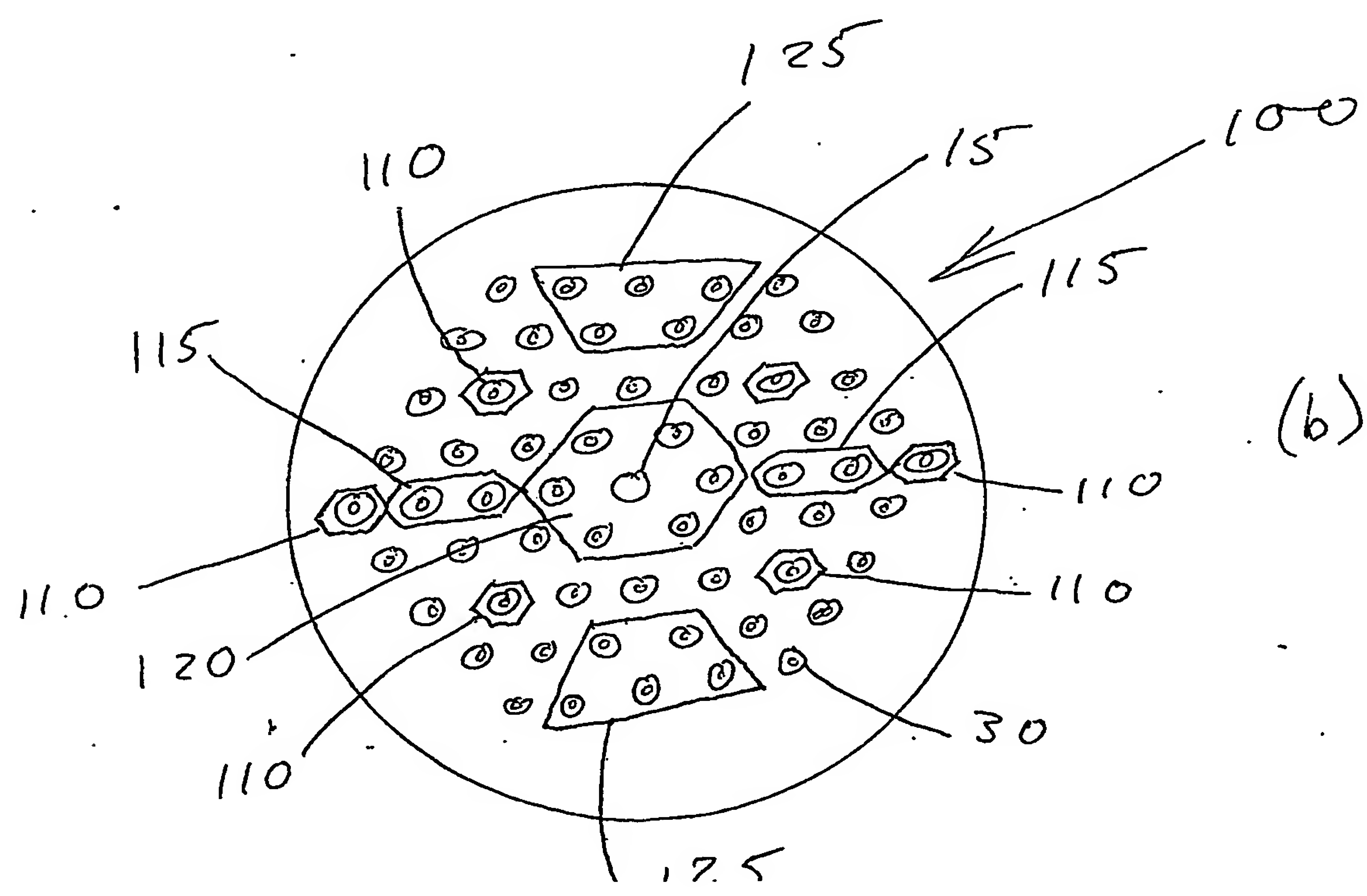
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(b)
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110
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30
110
125

FIG. 4

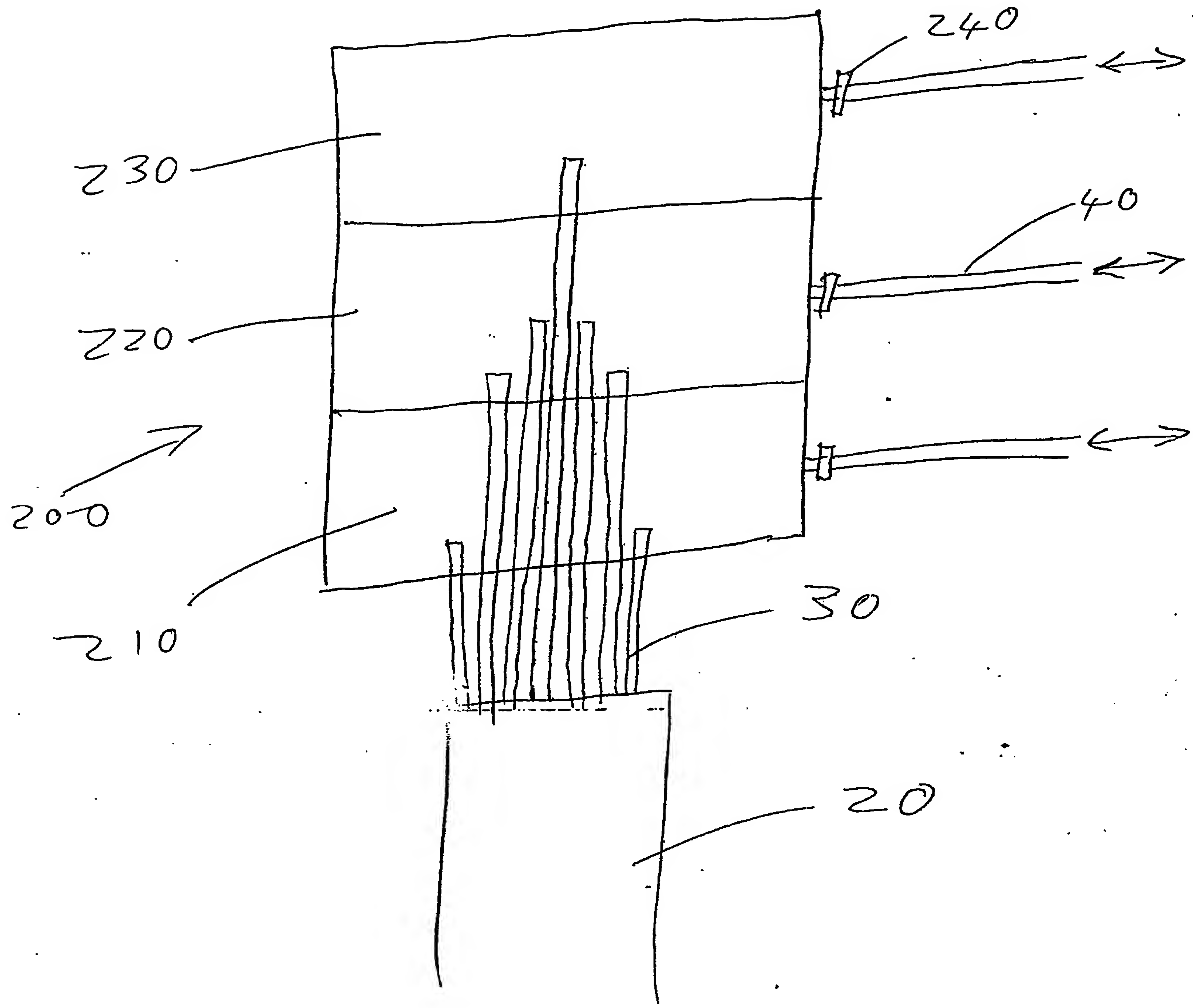


FIG. 5

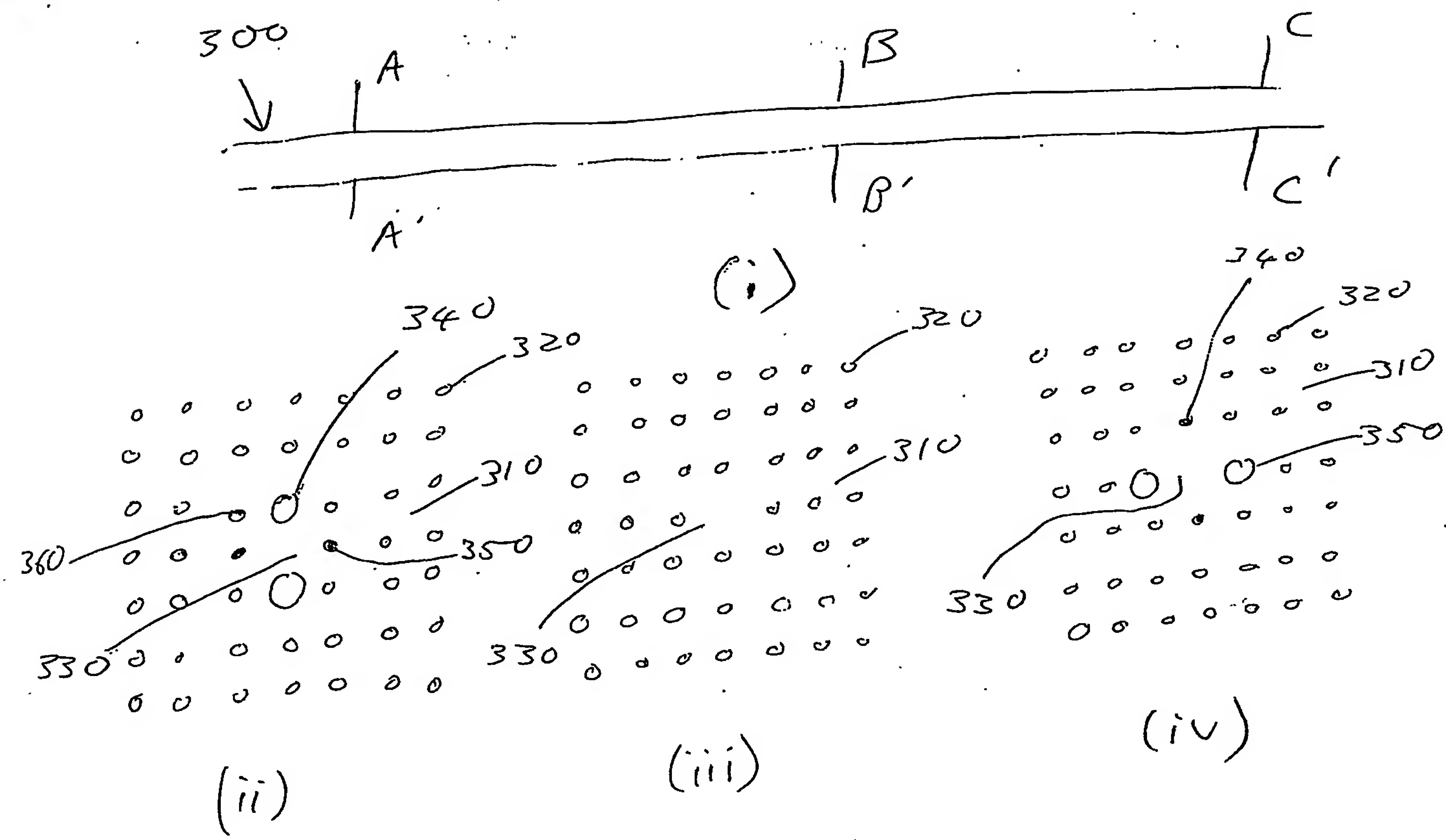
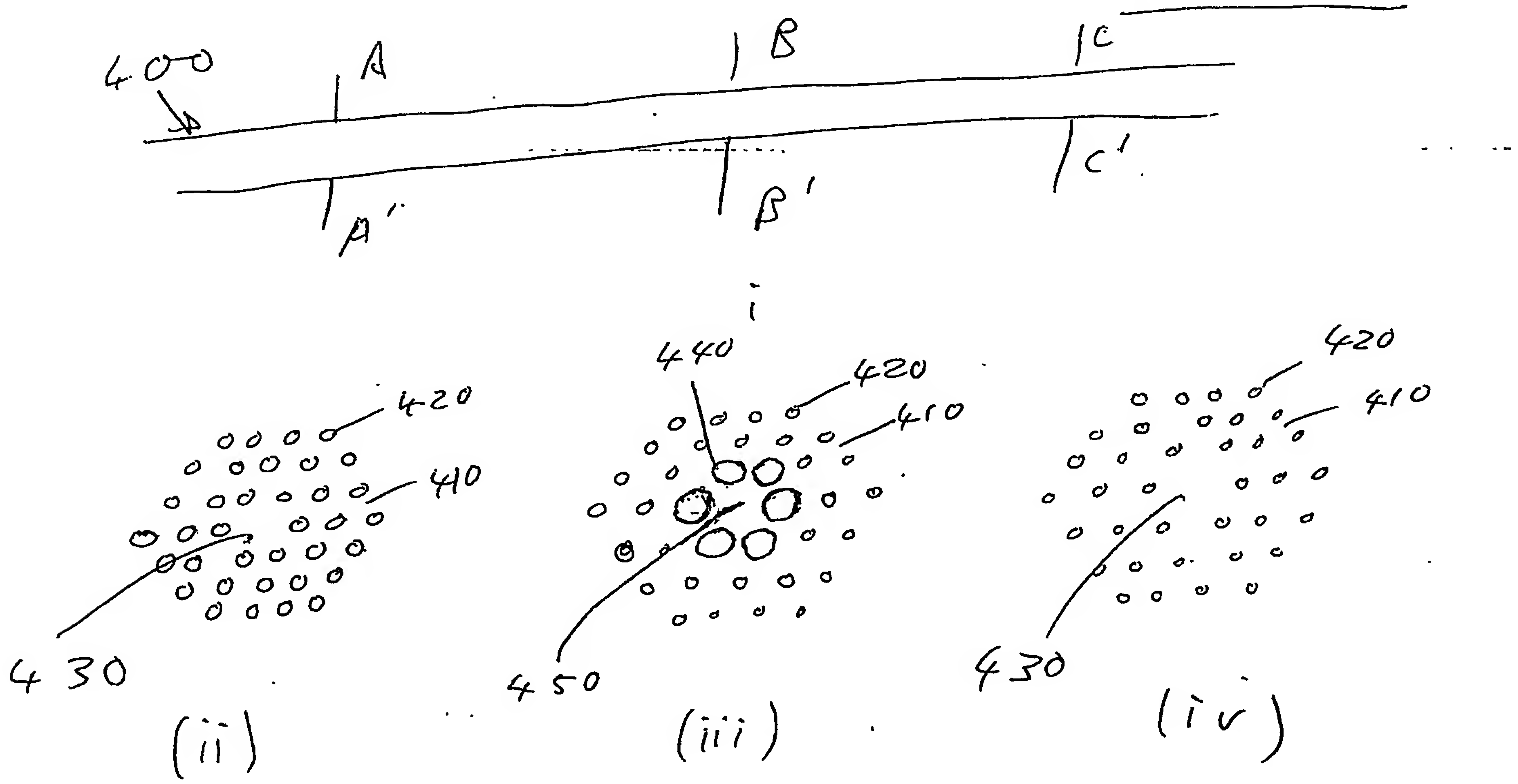

300
A
B
C
A'
B'
C'
(i)
340
320
310
360
350
330
(ii)
(iii)
(iv)

FIG. 6


400
A
B
C
A'
B'
C'
i
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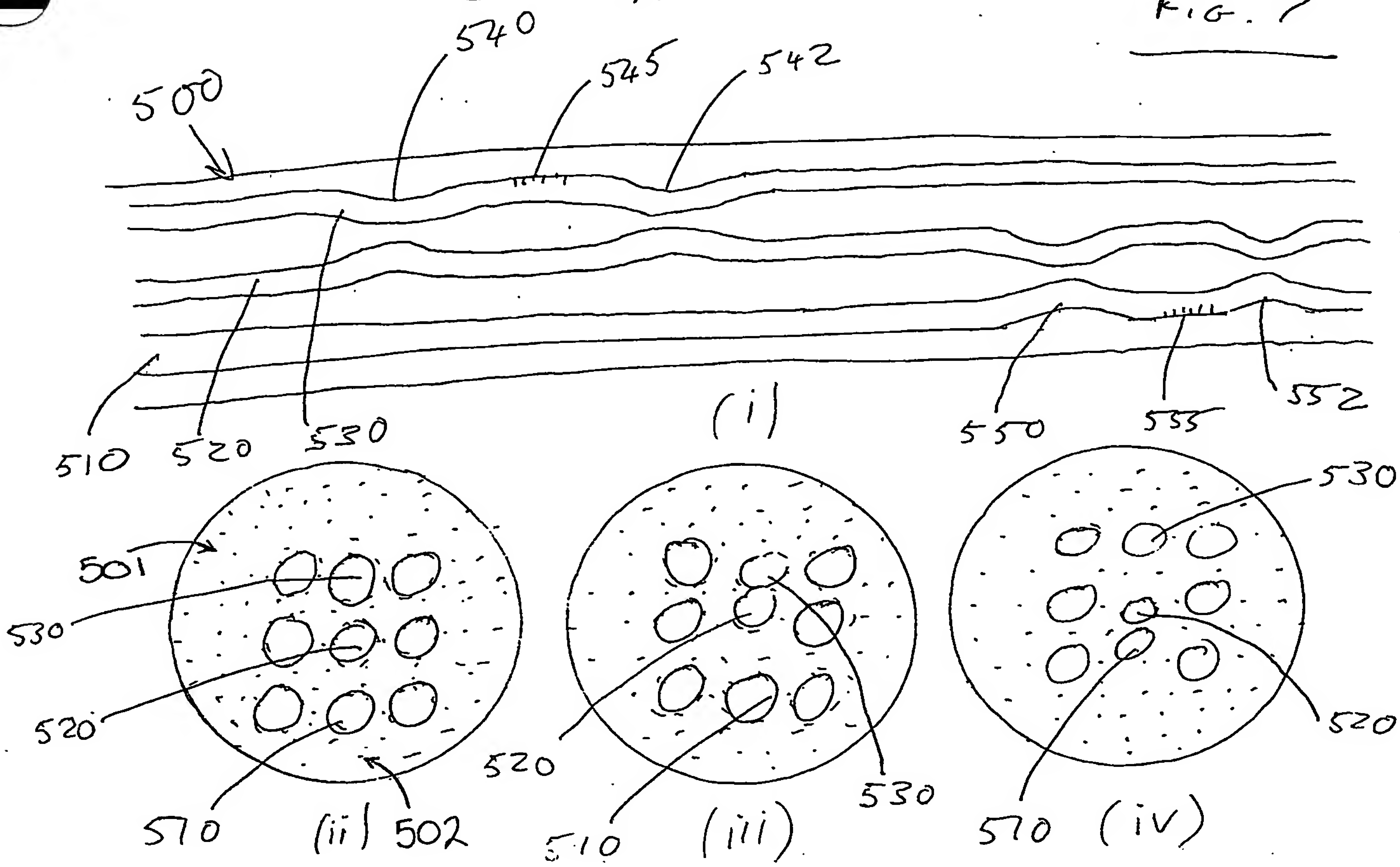
410
430
440
450
(ii)
(iii)
(iv)

Fig. 7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550
555
552
(i)
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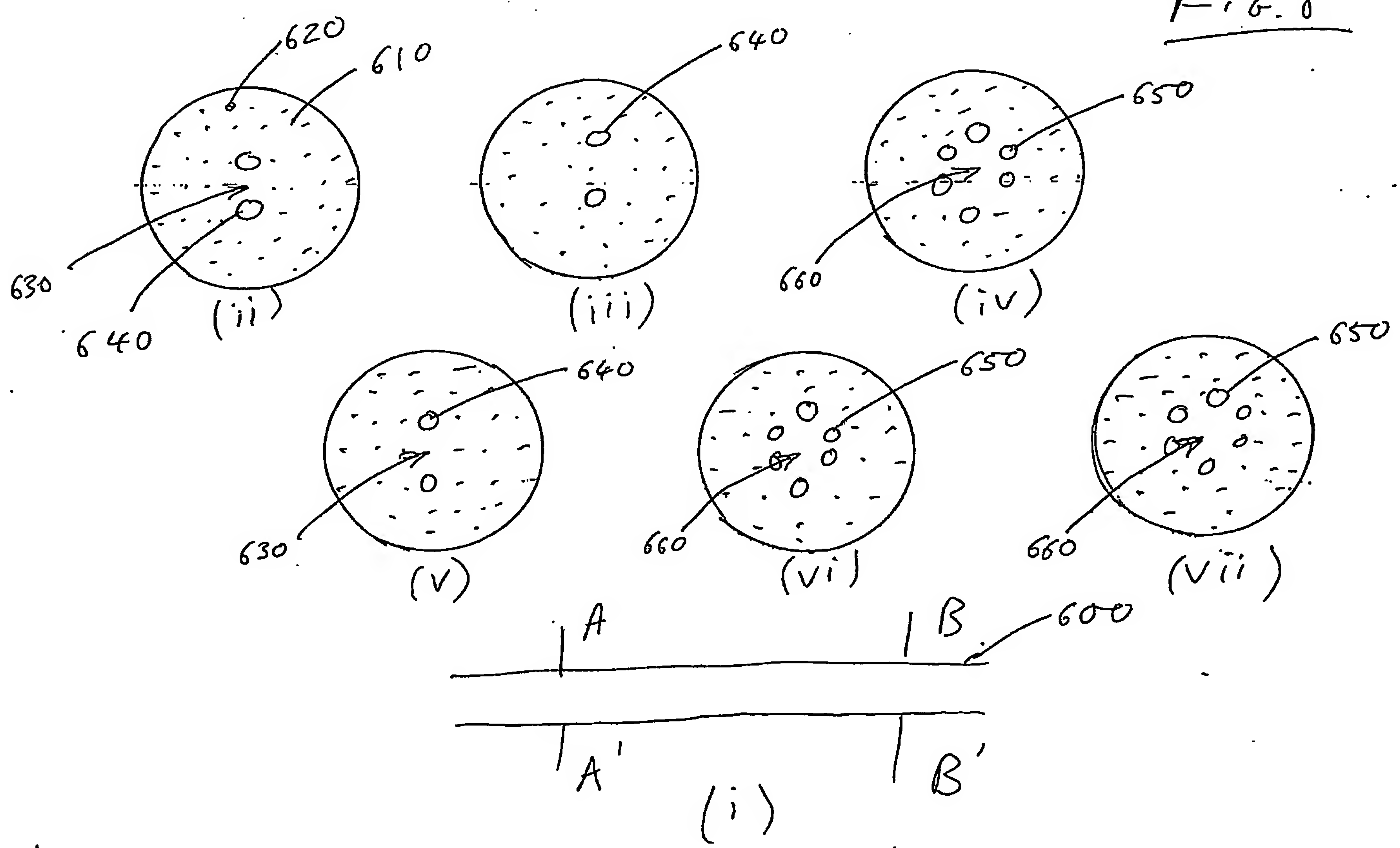
(ii)
502
520
510
(iii)
530
530
520
570
(iv)

Fig. 8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(iv)
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(v)
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(vi)
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(vii)
A
B
600
A'
B'
(i)